Active Uplift and Thrust-fault Strain Accumulation Rates from PS-InSAR and GPS data

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Annual Project Summary for FY2005 Activities

Constraining the kinematics and mechanics of active thrust faults from surface observations is a difficult task, plagued by limits in the quality and quantity of data, and inherent ambiguities in the determination of the deformation sources. This project addresses the seismic potential and natural hazard presented by thrust faults in the San Francisco Bay Area through the application and integration of highly precise space geodetic measurement techniques focused on areas of active uplift and convergence in the region. Our work to date suggests that we are taking the right approach towards tackling the development of a precise vertical velocity field in the region by incorporating InSAR and GPS data. We have focused our analysis on the uplift of (1) the Mt. Diablo thrust system, (2) the southern Santa Cruz Mountains along an SAF restraining bend, and (3) the East Bay Hills stepover region between the Hayward and Calaveras faults. We believe that we have been able to document tectonic uplift about these seismogenic thrust fault systems (Bürgmann et al., 2005, Geology). We are also analyzing the implications of rapid (≤ 3 mm/yr) 1992-2000 subsidence and contraction in the epicentral region of the 1989 Loma Prieta earthquake for the rheology of the lower crust and upper mantle under the Bay area. Our ongoing work focuses on (1) the comprehensive improvement, integration and analysis of PS-InSAR and GPS observations (2) the development of increasingly sophisticated and detailed models of crustal deformation, and (3) integration of geomorphic, geologic, and thermochronologic analyses that constrain where the dominantly elastic strain we measure may be released, possibly by seismic events.

1. Investigations Undertaken

The San Andreas fault (SAF) system in central California is a transform plate boundary accommodating ~38 mm/yr of right-lateral motion between the Pacific plate and the Sierra Nevada-Great Valley (SNGV) block (Argus and Gordon, 2001; d'Alessio et al., 2005). Regional contraction across the SAF system has occurred at rates of ~1-5 mm/yr since 3-5 Ma (Argus and Gordon, 2001). In addition to deformation associated with regional plate-normal convergence, high rates of shortening accommodated by thrust faulting occur in areas of restraining strike-slip fault geometries. In the San Francisco Bay area, a ~10° bend of the SAF through the Santa Cruz Mountains, the Mission Hills stepover region between the Calaveras and Hayward faults, and a left stepover between the Greenville and Concord faults (encompassing the Mt. Diablo anticlinorium) are areas of localized contraction and high topography (Fig. 1). Here, we use a new approach that allows us to determine a detailed image of vertical motions from non-tectonic and tectonic processes by combining precise, but sparsely distributed GPS-site motions with a large dataset of satellite-to ground range changes measured with synthetic aperture radar interferometry (InSAR). A first publication on this effort is now in press (Bürgmann et al., 2005).

Range-change rates recorded by the PS-InSAR measurements include the contribution of horizontal tectonic motions that project into the radar line-of-sight vector. To isolate the vertical component of the deformation, we use the GPS-derived horizontal velocity field to eliminate its contribution to each PS-InSAR range-change measurement. To this end, we use a 200-station subset of a regional 1993-2004 GPS velocity field (d'Alessio et al., 2005) to constrain a mechanical model of the horizontal deformation field. In the model, uniform-slip dislocations in an elastic half-space (Okada, 1985) reproduce the surface strain field about the Bay Area faults. Interseismic shear about a locked strike-slip fault is approximated by slip on a buried vertical screw dislocation extending deep below the seismogenic zone. Creep on the Hayward, southern Calaveras and the central San Andreas faults is modeled by shallow dislocation elements.

A simple 17-element dislocation model can explain much of the observed horizontal displacement field. The only large area that exhibits a systematic misfit pattern in the residual GPS velocities lies along the Loma Prieta section of the SAF, where a region of apparent residual contraction and right-lateral shear of ≤ 5 mm/yr is observed. The remaining high residuals are either apparent outliers or are located along creeping fault segments where more detailed, slip-distributed models are appropriate (Schmidt et al., 2005).

We use the modeled horizontal velocity field to calculate predicted range-change rates along the individually computed line-of-sight vectors due to horizontal motions at each InSAR data point. The modeled rates are then subtracted from the observed PS-InSAR rates. Scatter in the data at the level of about ± 0.5 mm/yr is probably in large part due to the inherent instability of the objects that reflect radar, which mostly consist of built structures.

Residual range-change rates represent the combined effects of horizontal and vertical motions that are unaccounted for by the tectonic dislocation model. Where non-tectonic horizontal displacement rates are small and the simplified velocity field produced by the dislocation model adequately represents the actual tectonic velocity field, the residual range-change rates may be interpreted in terms of vertical motions. In this case, the inferred vertical displacement rates are 1.08-1.10 times the residual range-change rate, a factor that slightly varies with the look angle across the area.

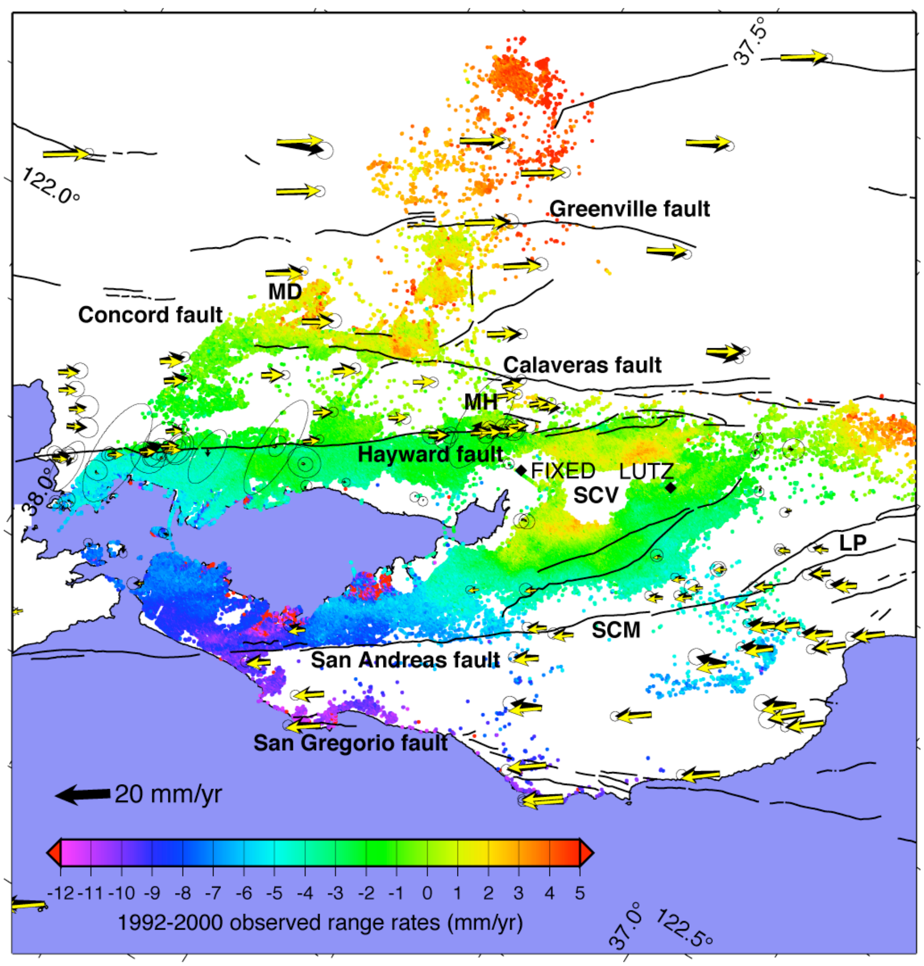

Figure 1. Fault map of Bay area in oblique Mercator projection about pole of Pacific-plate-to- SNGV block rotation. We include 199 1993-2003 GPS velocities (black arrows tipped with 95% confidence ellipses, not all in map frame) relative to station LUTZ. Yellow arrows are velocities from dislocation model. Color-scaled dots show 1992-2000 PS-InSAR range-change rates relative to point labeled FIXED. LP, Loma Prieta; MD, Mt. Diablo; MH, Mission Hills; SCM, Santa Cruz Mountains; SCV, Santa Clara Valley.

2. Results

When the range-change contribution due to horizontal tectonic motions is removed from the data, we find that the largest motions revealed in the PS-InSAR data are due to various non-tectonic hydrological and surface processes. Many of the non-tectonic features are highly localized including active landslides (Hilley et al., 2004) and localized subsidence along the Bay due to consolidation of manmade fill and Bay mud (Ferretti et al., 2004). Regions of uplift overlie young sedimentary basins that are expanding due to increasing groundwater levels during the observation period (Schmidt and Bürgmann, 2003).

To resolve tectonic deformation, we identify points in the dataset in which these non-tectonic processes severely influence the deformation measurement. The PS-InSAR data suggest that points located on Quaternary substrate are generally more likely to record deformation related to non-tectonic processes, and so we use a GIS-produced map of the distribution of Quaternary units in the region (Knudsen et al., 2000), to separate 92,102 points located on Quaternary units from those on bedrock (i.e., non-Quaternary) (Fig. 2).

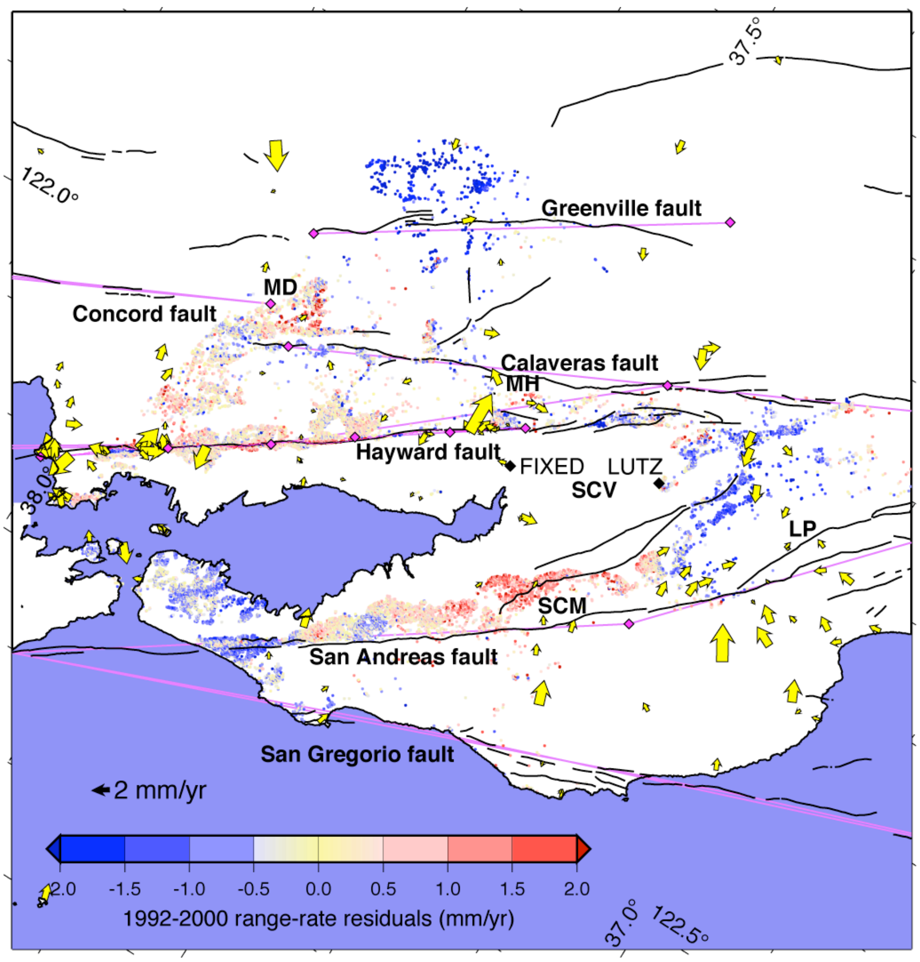

Figure 2. Residual PS-InSAR rates after removing contribution of tectonic horizontal motions and all points located on Quaternary substrate. Inferred uplift rates are 1.08-1.10 times the range-change rates depicted, assuming that all remaining deformation is due to vertical motions (positive range-rate residuals correspond to uplift). Yellow arrows are GPS residual (observed minus modeled) horizontal velocities and pink lines and diamonds are vertical model dislocation planes and their ends, respectively.

When interpreted in terms of vertical motions, the residual range-change rate field of bedrock target points includes three larger areas of subsidence and three regions of uplift at 0.5-1.5 mm/yr rates (Fig. 2). One area of apparent subsidence is located east of the Greenville fault and we have no obvious explanation for this feature. The second area of subsidence at rates of up to ~2 mm/yr appears localized about the epicentral region of the 1989, Mw = 6.9 Loma Prieta earthquake and coincides with the region of horizontal contraction evident in the residual GPS velocities. The direction and magnitude of these residual horizontal velocities can explain only ~0.5 mm/yr of the residual range-change rate and subsidence at ~1.5 mm/yr is indicated. Such subsidence is expected due to continued postseismic relaxation at depth following the Loma Prieta earthquake (Pollitz et al., 1998). We are currently working on modeling these data to better constrain the rheology in the lower crust and upper mantle. A third zone of slow (~0.5 mm/yr) subsidence along the northern San Francisco peninsula may be related to an extensional bend in the SAF and/or interaction with the offshore San Gregorio fault zone.

Uplift rates of the order of 1 mm/yr are indicated along the southern Santa Cruz Mountains that flank Santa Clara Valley, along the peak elevations of the Mission Hills and within the southern foothills of Mt. Diablo. Inferred uplift is observed on both sides of the SAF between 37°10’ and 37°30’ latitude, but appears to be highest to the northeast overlying a number of Quaternary thrust faults (Bürgmann et al., 1994). As the Santa Cruz Mountain uplift zone is adjoined by the rapidly expanding Santa Clara aquifer, we are not able to fully characterize the shape of the uplift zone or develop a well-constrained mechanical model of the deformation. The uplift is terminated to the southeast by the Loma Prieta zone of subsidence and residual contraction. Overall, the data suggest that uplift occurs over a broad zone, consistent with regional contraction along the restraining bend in the SAF that is ultimately accommodated by discrete thrust faulting and folding. Points located between the Hayward and Calaveras faults appear to be rising at rates of 0-1.5 mm/yr. The highest uplift rates are localized in a small zone coinciding with the highest elevations of the Mission Hills (Fig. 2).

Our study shows how contributions from non-tectonic processes and time-dependent earthquake cycle deformation make the identification of active, vertical tectonics from geodetic data a challenging endeavor. The largest vertical motions are due to non-tectonic processes such as land sliding, groundwater-level changes and sediment settling. If we exclude all data points located on Quaternary substrate to limit contributions to the deformation signal from non-tectonic motions, the InSAR range-change rates corrected for horizontal tectonic motions reflect vertical deformation rates in the region that are < 2 mm/yr. The joint use of continuous GPS and multiple PS-InSAR datasets obtained from different acquisition geometries and radar satellites will allow for future improvements in the accuracy of space-geodetic uplift measurements.

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3. Non-technical Summary

This project addresses the seismic potential and natural hazard presented by thrust faults in the San Francisco Bay Area. Our approach is to integrate highly precise, space geodetic measurement techniques (the Global Positioning System, GPS and interferometric synthetic aperture radar, InSAR) to determine areas of active uplift and convergence in the region. Our work to date suggests active uplift at ≤ 2 mm/yr of the Mt. Diablo thrust system, the southern Santa Cruz Mountains along a bend of the San Andreas fault, and the East Bay Hills stepover region between the Hayward and Calaveras faults. We also find rapid (≤ 3 mm/yr) 1992-2000 subsidence and contraction in the epicentral region of the 1989 Loma Prieta earthquake which appears to be the result of continued viscous relaxation of the upper mantle caused by the earthquake.

4. Reports Published

Bürgmann, R., G. Hilley, A. Ferretti, and F. Novali (2005), Resolving Vertical Tectonics in the San Francisco Bay Area from Permanent Scatterer InSAR and GPS Analysis, Geology, in press.

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6. Data Availability

Raw and RINEX formatted GPS data files for static surveys of markers in the San Francisco Bay area from 1994-2004. These files typically include greater than six continuous hours of data, recorded at a 30 s collection rate with a 10-degree elevation mask. These data are freely available through the UNAVCO archive facility in Boulder, and also at the University of California, Berkeley. http://archive.unavco.ucar.edu/cgi-bin/dmg/groups?cpn=1&oby=group_name
Data collected by our group for this project are archived under the Group Names of “Calaveras Fault”, “Hayward Fault” and “Loma Prieta.”

Photocopies of survey log sheets and site descriptions are also available. Additional data used in this study included RINEX format files obtained from the U.S. Geological Survey and the Bay Area Regional Deformation Network (BARD). These files include campaign-style surveying (USGS) and continuous GPS stations (BARD) and are available at the NCEDC at UC Berkeley.

For more information regarding data availability, contact:
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InSAR data (copyrighted by ESA) used in this project are available via the WInSAR archive, supported in part by the USGS. Range change rate results can be requested via e-mail to Roland Bürgmann.